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Size effect on the electrical resistivity of aluminium, indium and thallium films

V S Pankajakshan and K Neelakandan

Department of Physics, University of Calicut, Kerala-673 635, India

and

C S Menon

Department of Materials Science, Mahatma Gandhi University, Kottayam-686 002, Kerala, India

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Abstract : *In situ* electrical resistivity measurements are made on vacuum deposited aluminium, indium and thallium thin films of different thicknesses at room temperature. The variation of resistivity with thickness is used to find the bulk resistivity and electron mean free path of these metals by employing Fuchs-Sondheimer theory. The free electron density and the Fermi surface area of aluminium, indium and thallium are also calculated and compared with earlier measurements.

Keywords : Thin metal films, size effect, Fuchs-Sondheimer theory.

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1. Introduction

The electrical conductivity of thin metal film depends upon its temperature, structure and thickness. If the thickness is less than the mean free path of the conduction electrons in the bulk metal then the surface behaves as a structural imperfection and the motion of the conduction electrons is affected. The dependence of electrical resistivity on thickness is often referred to as size effect (Mayadas and Shatzkes 1970, Coutts 1971, Sambles 1983, Damodara Das and Soundarajan 1987). In the present work, the measurement of electrical resistivity during the growth of aluminium, indium and thallium thin films have been made at room temperature. The bulk resistivity ρ_0 and mean free path λ of conduction electrons are calculated. The present work is compared with the earlier measurements on aluminium (Tochitskii and Belyavskii 1980), indium (Pal and Chaudhuri 1976, Stolecki *et al* 1984) and thallium (Rahman and Mahanta 1979).

2. Theory

The mean free path of conduction electrons influences the resistivity of metals and its value depends upon the crystal lattice perturbations caused by thermal motion and structural defects. The analysis of size effect was made by Fuchs (1938) solving Boltzmann transport equation with appropriate boundary conditions and later modified by Sondheimer (1952). According to Fuchs-Sondheimer theory, the film resistivity ρ as a function of thickness d can be expressed, when

$$k = d/\lambda > 1, \text{ as}$$

$$\rho d = \rho_0[d + (3/8)\lambda(1 - p)] \tag{1}$$

where p is the specularity parameter for electron reflection from the film surface. From eq. (1), it can be seen that a plot of ρd versus d should be straight line. The mean free path can be calculated from the intercept and the slope gives ρ_0. If the scattering of the electrons from the film surface is assumed to be entirely diffuse in nature, then p can be taken as zero. The Fermi surface area A and the free electrons density n are related in the following manner (Chopra 1969)

$$\frac{1}{\rho_0 \lambda} = \frac{e^2 A}{6\pi^2 h} = \left(\frac{8\pi}{3}\right)^{1/3} \left(\frac{e}{h}\right)^2 n^{2/3} \tag{2}$$

where e and h are electron charge and Planck's constant respectively.

3. Experiment

Aluminium, indium and thallium films were grown by thermal evaporation at a pressure of 2×10^{-6} torr (Pankajakshan *et al* 1989). High purity aluminium (99.999%), indium (99.99%) and thallium (99.99%) were evaporated using tungsten helical coil, molybdenum and tantalum boats respectively onto masked areas of glass substrates kept at room temperature at a pressure of 2×10^{-6} torr. Film thickness was monitored by a calibrated quartz crystal thickness monitor having an accuracy of 10 Å and resistance was measured by four probe method using the set-up described elsewhere (Menon and Pankajakshan 1987). Thickness and resistance were measured *in situ* to minimize oxidation of the film surface. The length l, and width w of all the films used were 32 mm × 1.5 mm. The resistivity has been calculated using the relation $\rho = Rdw/l$ were R is the resistance of the film.

4. Results and discussion

The variation of resistivity as a function of thickness for aluminium, indium and thallium films are given in Figures 1, 2 and 3 respectively. The resistivity at first decreases rapidly with increase in thickness but remains almost steady afterwards. The films become conducting at thickness of 50 Å, 200 Å and 380 Å for aluminium, indium and thallium respectively. The values of ρ_0 and λ are found out from the slope and intercept of Figures 4, 5 and 6. They are used to calculate the Fermi surface area and free electron density from eq. (2) and are collected in Table 1.

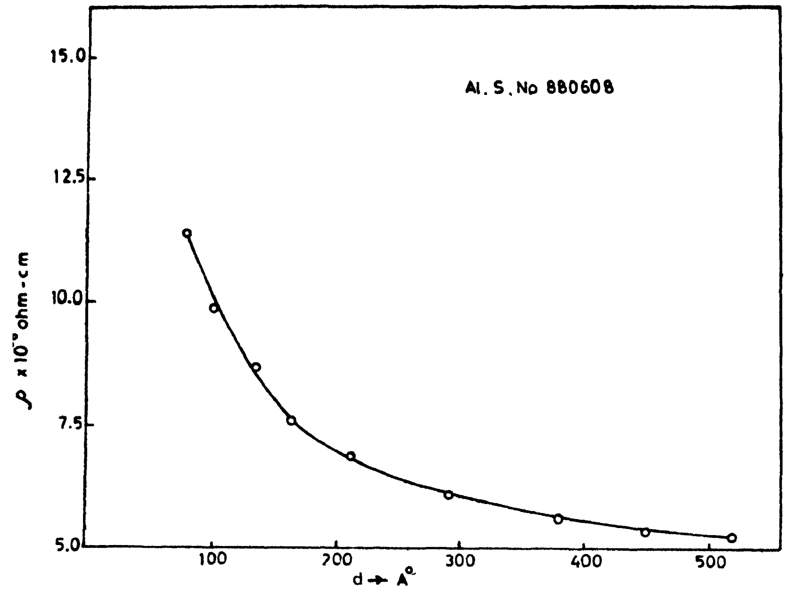

Figure 1. Variation of electrical resistivity with thickness for aluminium.

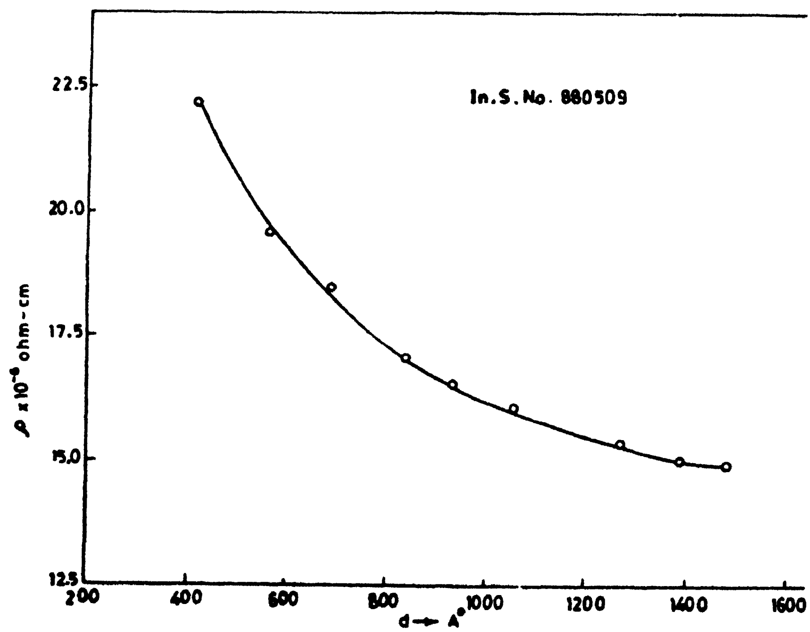

Figure 2. Variation of electrical resistivity with thickness for indium.

The values of ρ_0, λ, n and A are compared with available values reported and are also given in Table 1.

It may be noted that bluk resistivities calculated for these films are rather high when compared with those of Kittel (1974) ; but are of the same order as

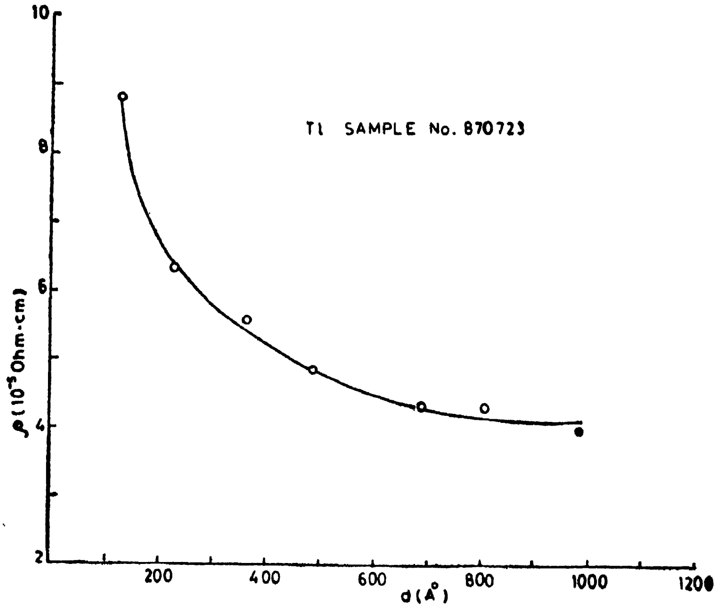

Figure 3. Variation of electrical resistivity with thickness for thallium.

that obtained by other workers. The thickness dependence of resistivity is attributed to surface scattering (Sambles 1983). The pressure of 2×10^{-5} torr, at which the measurements are made does not exclude the possibility of the residual

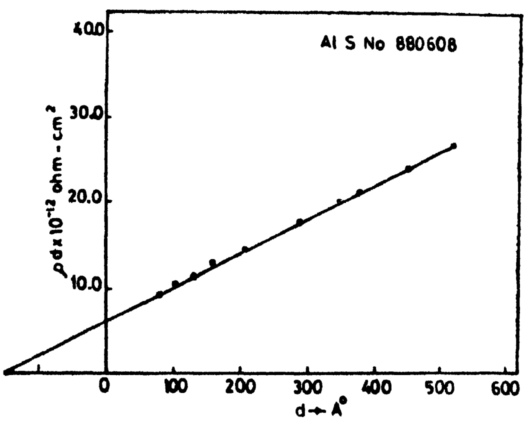

Figure 4. ρd versus d for aluminium.

gas molecules in the chamber influencing the conductivity of the films. The resistivity of surface layer that has reacted with the residual gas will be larger than that of the metal film, even though the conductivity of the surface layer is still

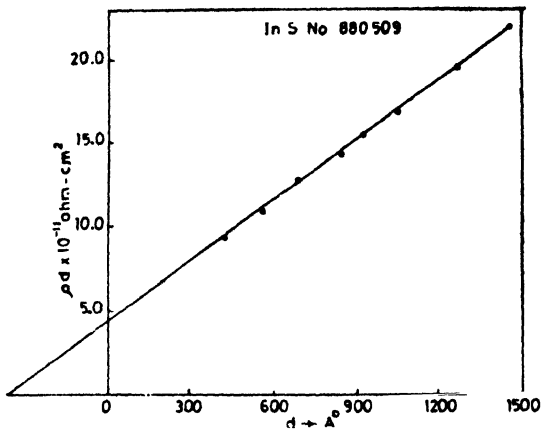

Figure 5. ρd versus d for indium.

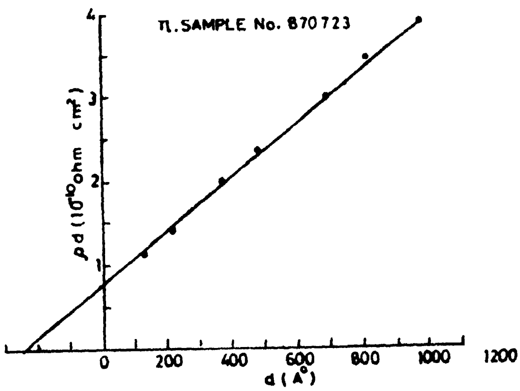

Figure 6. ρd versus d for thallium.

metallic in nature. The adsorbed gas molecules act as additional scattering centres for the conduction electrons and hence contribute to the increase in resistivity.

Table 1. Values of bulk resistivity ρ_0, mean free path λ, Fermi surface area A and free electron density n of aluminium, indium and thallium compared with previously reported values, given in bracket and its reference.

Metal	$\rho_0 \times 10^{-6}$ ohm – cm	$\lambda \times 10^{-8}$ cm	$A \times 10^{16}$ cm^{-2}	n cm^{-3}
Aluminium	3.92 (2.74)*	411 (304)†	9.48	2.213×10^{22}
Indium	11.76 (11.87+, 8.75*)	960 (996+)	1.35	1.19×10^{21}
Thallium	33.0 (37.0ª, 16.4*)	587 (640ª)	0.79 (0.651ª)	5.32×10^{20} (3.98×10^{20}ª)

*Kittel (1974), +Pal and Chaudhuri (1976), †Tochitskii and Belyavskii (1980), ªRahman and Mahanta (1979).

5. Conclusion

Aluminium, indium and thallium films evaporated onto glass substrates show size effect. Fuchs-Sondheimer theory was used to find bulk resistivity and mean free path. The Fermi surface area and free electron density are calculated for these metals.

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